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A PRELIMINARY STUDY OF THE FEASIBILITY OF USING A PRESURIZED TUBE FOR THE SOFT RECOVERY OF A FIVE INCH PROJECTILE

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Naval Weapons Laboratory
Dahlgren, Virginia

November 1973

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This report presents the results of a preliminary study of the possibility of using a pressurized tube to recover a standard five inch projectile with projectile decelerations no greater than 10% of the maximum in-bore acceleration. Computer calculations using both a simplified dynamics model and a one-dimensional Lagrangian hydrocode have been performed for a variety of recovery tube gases, initial pressures and tube lengths. Calculations were also made for tubes vented by blowing

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plugs out of the ends. Results of the calculations indicate that an initial pressurization of five to seven atmospheres is required to stop the projectile within the 10% limitation if a dense gas such as Sulfur Hexafluride or Freon 12 is used. The required tube length is approximately 300 feet.

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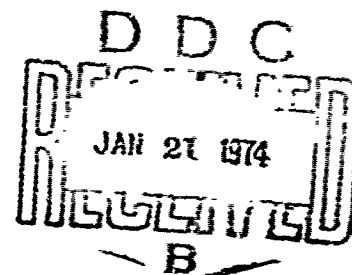A PRELIMINARY STUDY OF THE FEASIBILITY

OF USING A PRESSURIZED TUBE FOR THE SOFT

RECOVERY OF A FIVE INCH PROJECTILE

by

L. P. Anderson, Jr.

Test and Evaluation Department

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FOREWORD

This report presents the results of a preliminary study of the
feasibility of using a pressurized tube to softly recover a five inch
projectile. This work was performed as a portion of the Naval Weapons
Laboratory Independent Research/Independent Exploratory Development
Program.

This report was reviewed by J. J. Yagle and W. J. Lewis of the
Test and Evaluation Department.

Released by:

LEE A. CLAYBERG, Head,
Test and Evaluation Department

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ABSTRACT

This report presents the results of a preliminary study of the possibility of using a pressurized tube to recover a standard five inch projectile with projectile decelerations no greater than 10% of the maximum in-bore acceleration. Computer calculations using both a simplified dynamics model and a one-dimensional Lagrangian hydrocode have been performed for a variety of recovery tube gases, initial pressures and tube lengths. Calculations were also made for tubes vented by blowing plugs out of the ends. Results of the calculations indicate that an initial pressurization of five to seven atmospheres is required to stop the projectile within the 10% limitation if a dense gas such as Sulfur Hexafluoride or Freon 12 is used. The required tube length is approximately 300 feet.

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1. INTRODUCTION

The most frequently used method of recovering five inch projectiles at NWL is sawdust recovery. The projectiles are fired into railroad cars filled with sawdust. This method is less than satisfactory because it is time consuming and imparts very high deceleration to the projectile. Because the frequency of required soft recoveries is large, it is highly desirable to have a permanent facility that would allow projectiles to be stopped with a low deceleration and recovered rapidly and inexpensively.

The purpose of this report is to describe an initial feasibility study of a pressurized tube method for recovering five inch projectiles. This method of recovery would use a tube filled with a pressurized gas to recover a projectile fired from a standard five inch gun.

The concept of a pressurized recovery tube is not new. Computer studies of this method used to recover 155mm projectiles are described in reference (1). The analysis described in reference (1) assumes the projectile is decelerated completely by isentropic compression and there are no pressure gradients in the recovery tube gas. However, the present studies show the propagation of shocks in the gas greatly influences the recovery, causing the results to differ greatly from those which assume an isentropic compression. The present study also reveals the desirability of using dense gases in the recovery tube and a plug method for venting the gases. The basic concept of a pressurized recovery tube is also found in the "Super G Shock Facility" used by Sanders Associates for testing components of 90mm projectiles, reference (2). No experimental or theoretical data have been obtained on the projectile motion of this facility.

This report is organized as follows: Section II uses the results of a simplified analysis to discuss the essential characteristics of the recovery process. Section III presents the results of a more accurate model based on a one-dimensional Lagrangian hydrocode. Calculations are performed for a tube filled with Sulfur Hexafluoride, and vented by means of a plug at the end. Section IV gives conclusions, discusses the limitations of the present theory, and the need for further study.

On the basis of the results described in this report, it is concluded that it is possible to recover a standard five inch projectile with decelerations no greater than 10% of the maximum in-bore acceleration by means of a 300 feet long tube. An initial recovery tube pressure of 30 atmospheres is required if air is used in the recovery tube; while a pressure of five to seven atmospheres is required if a dense gas such as Sulfur Hexafluoride or Freon 12 is used.

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## II. BASIC DESCRIPTION OF RECOVERY PRINCIPLES FOR A CLOSED TUBE

To understand the basic physical principles involved in slowing down a projectile in a tube of compressed gas, the motion of a projectile in a closed end tube will be examined in this section. This study uses the results of a simplified theoretical model and provides insight into the dependence of the projectile motion on such physical parameters as initial tube pressure, properties of the tube gas, and the tube length. The theoretical model does not account for wave motion in the recovery gas completely, but provides a considerable improvement over the previous isentropic compression models. The analysis in the next section treats all wave motion in the recovery gas with great accuracy, but does not provide as much physical insight to the recovery process as the following theoretical model.

A. Influence of Shock Waves

Consider a five inch projectile leaving a gun with muzzle velocity, V_0, and entering a tube of compressed gas (see Figure 1). Assume that:

1. There is no leakage of gas past the projectile.

2. The pressure on the base of the projectile is atmospheric.

3. The mu: d of the tube is closed.

In this situation, the projectile acts as a piston which suddenly accelerates the gas ahead of it to velocity, V_0. This sudden movement of gas causes a shock wave to be propagated in front of the projectile. Thus, the initial deceleration of the projectile will be caused by the pressure behind the shock wave. This pressure, P_s, will be greater than the initial tube pressure by the factor, $\xi = P_s/P_0$, where P_s is the pressure behind the shock wave, P_0 is the initial tube pressure. The quantity, ξ, is called the shock strength. As the projectile slows down, it will cause the volume of gas between it and the shock wave to increase, thereby, reducing the pressure in front of the projectile and the strength of the shock. Reduction of pressure on the front of the projectile will cause its deceleration to decrease. When the shock reaches the closed end of the tube, it will be reflected toward the oncoming projectile. From this point in time, multiple shock reflections will occur between the projectile and the end of the tube. Each time a shock reflects from the front of the projectile, it causes an increase in the deceleration. Eventually, the projectile will achieve zero velocity. Because of the increased pressure due to the shock reflections, it will begin to move in the opposite direction. The trajectories of both the projectile and the shock wave are shown in Figure 2, where x is distance and t is time.

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HIGH PRESSURE GAS

RECOVERY TUBE

PROJECTILE

FIVE INCH GUN
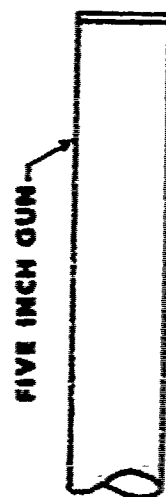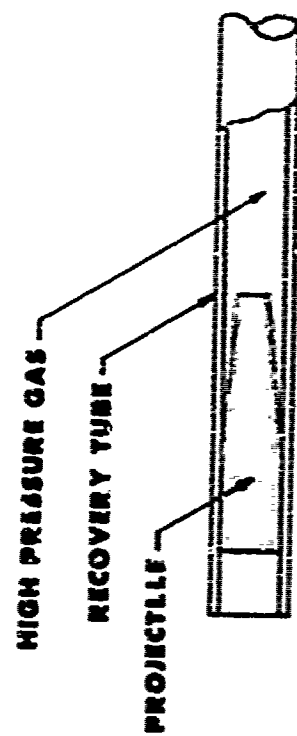
PROJECTILE RECOVERY METHOD

FIGURE 1

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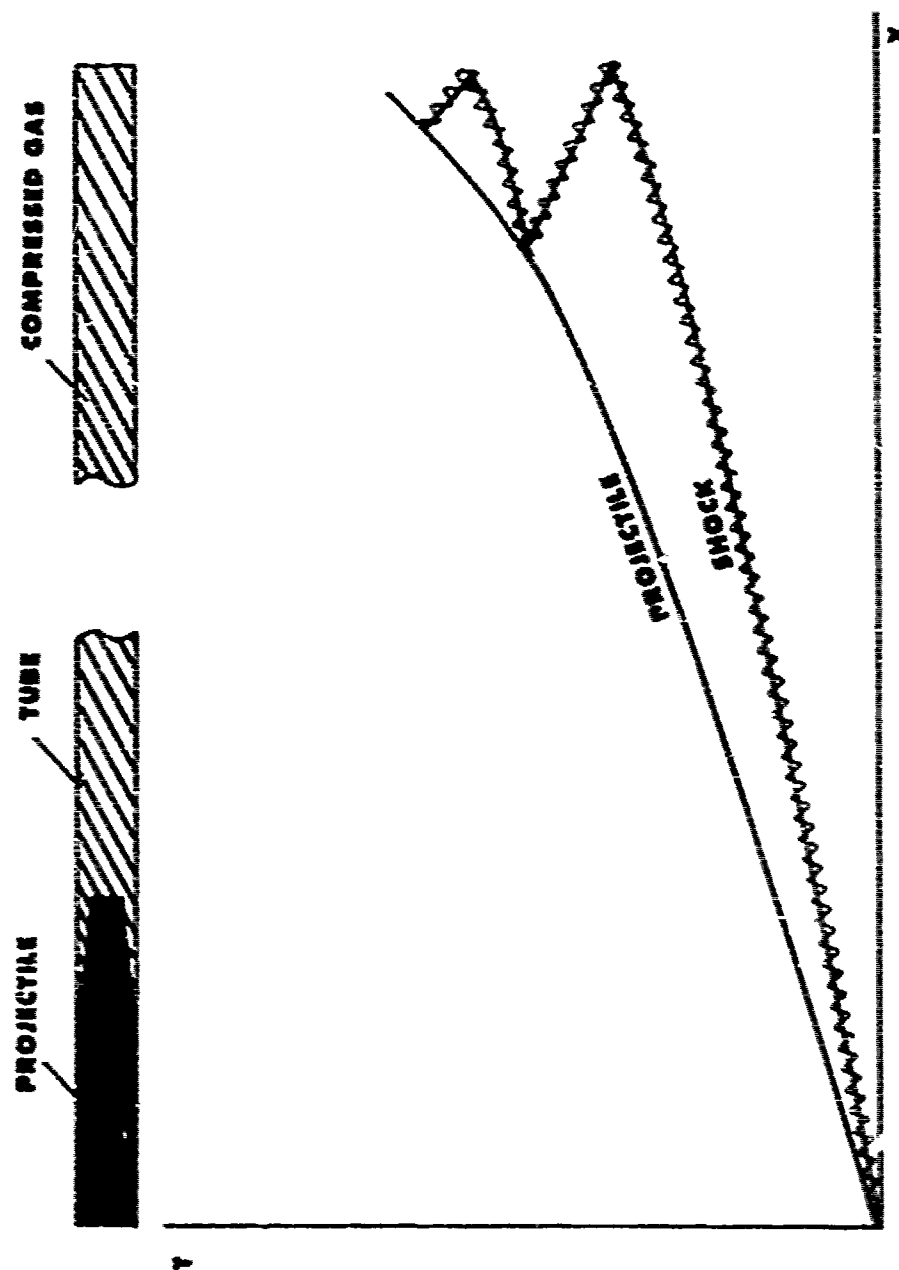
TRAJECTORIES OF PROJECTILE AND SHOCK WAVES

FIGURE 2

Labels in figure: COMPRESSED GAS, TUBE, PROJECTILE, PROJECTILE, SHOCK, X, Y

B. Analysis of Projectile Motion

If it is assumed the flow properties at the front of the projectile are the same as those at the shock front for any given time, i.e., no pressure gradients exist between the shock front and the projectile, then:

$$U_p = U_s = \frac{(\xi - 1)\, a_0}{\gamma\sqrt{1 + \frac{(\gamma + 1)}{(2\gamma)}\,(\xi - 1)}} \tag{1}$$

where, U_p is the velocity of the projectile[1], U_s is the gas velocity at the shock front, a_0 is the sound speed in front of shock, and γ is the specific heat ratio of the recovery tube gas. The force on the projectile is related to its deceleration by,

$$D_p = -\frac{d\,U_p}{dt} = \frac{A}{M}\,(\xi P_0 - P_b) \tag{2}$$

where, D_p is the deceleration of the projectile, A is the area of the projectile base (assumed to be the same as the tube cross section), M is the projectile mass and P_b is the pressure on the projectile base (assumed to be a constant 14.7 psi). Solving equation (1) for ξ and substituting into equation (2) gives,

$$\frac{d\,U_p}{dt} = \frac{A}{M}\,P_b - \frac{A}{M}\,P_0\,\{\frac{\gamma}{4}\frac{U_p}{a_0}\left[(\gamma + 1)\frac{U_p}{a_0} - \sqrt{(\gamma + 1)^2\frac{U_p^2}{a_0^2} + 16}\right] + 1\} \tag{3}$$

Equation (3) is a nonlinear, first order, ordinary differential equation which can be integrated numerically to give the velocity and the position of the projectile at any time, t. The corresponding velocity of the shock front can be calculated from the Rankine-Hugoniot equation:

$$V_s = \frac{d\,X_s}{dt} = a_0\,\sqrt{\frac{\frac{\gamma - 1}{\gamma + 1} + \xi}{\frac{\gamma - 1}{\gamma + 1} + 1}} \tag{4}$$

where X_s and V_s are the position and the velocity of the shock front, respectively. Integration of equation (4) gives the shock front

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[1] A projectile speed of 3000 ft/sec is used throughout this report.

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position. The other flow properties behind the shock are given by the appropriate Rankine-Hugoniot relations. For example, the sound speed is given by:

$$a_s = a_0 \sqrt{-\frac{\{1 + [(\gamma - 1)/(\gamma + 1)]\xi\}\xi}{(\gamma - 1)/(\gamma + 1) + \xi}} \qquad (5)$$

where a_s is the sound speed behind the shock.

The deceleration of the projectile and the properties behind the shock can be calculated from equations (1) through (5) until the shock reflects from the end of the recovery tube. The strength of the reflected shock is determined by,

$$\xi_r = P_r/P_s = \frac{(1 + 2\frac{\gamma - 1}{\gamma + 1})\xi - \frac{\gamma - 1}{\gamma + 1}}{1 + \frac{\gamma - 1}{\gamma + 1}\xi} \qquad (6)$$

where ξ_r and P_r are the strength of and the pressure behind the reflected shock. The reflected shock travels upstream until it collides with the projectile, where it again undergoes reflection. The strength of the reflected shock is determined by equation (1) when the appropriate values for the sound speed and the projectile velocity are used.

A repetition of the above procedure, using equations (1) through (6), with the appropriate values, determines the effects of the multiple reflections. The entire procedure can be carried out until the projectile velocity becomes zero.

The above calculation procedure has been programmed for the CDC 6700 computer at NWL. A typical projectile deceleration versus time curve is shown in Figure 3. The results shown in the figure are from a computer run for a 250 foot tube filled with air at an initial pressure of 30 atmospheres. For this case, only one reflection occurs on the face of the projectile before it stops.

From the above discussion and Figure 3, it is seen that the maximum deceleration of the projectile will be caused by either the initial shock or the one or more reflected shocks. Throughout the rest of this report, these two maxima will be referred to as the initial deceleration and the reflection deceleration, respectively.

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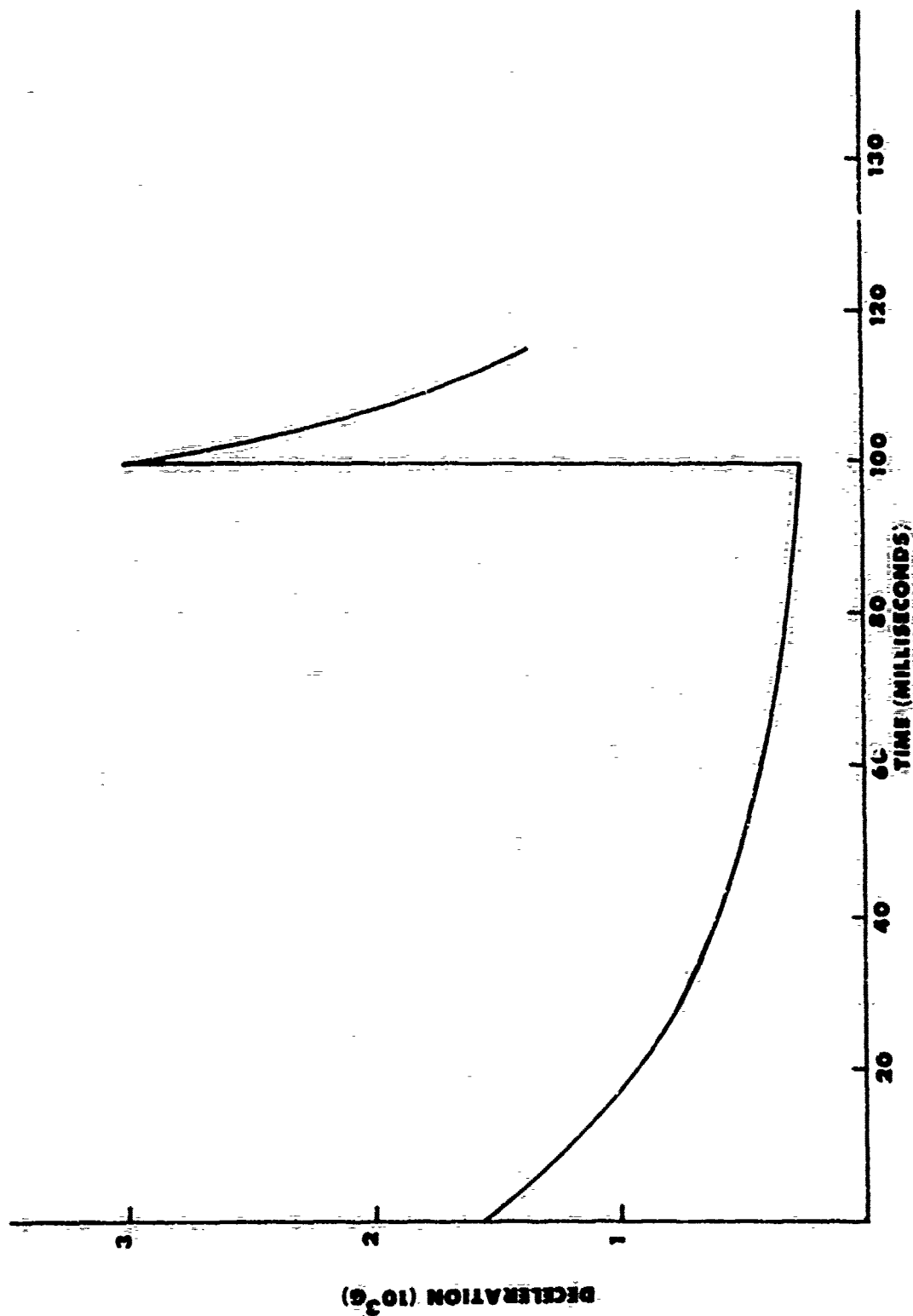
TYPICAL DECELERATION VS TIME FOR CLOSED END
RECOVERY TUBE
FIGURE 3

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C. Effects of Various Parameters

The computer program mentioned above was used to study the effects on the maximum deceleration due to varying the specific heat ratio, initial sound speed[2], initial pressure of the recovery tube gas, and tube length. In each case, one parameter was varied while the other three were held constant. Typical examples, obtained from the study are illustrated below:

1. Specific Heat Ratio

Increasing the specific heat ratio, increases the strength of the initial shock, thus increasing the initial deceleration. Since the projectile velocity decreases at a faster rate, the strength of the initial shock decreases at a faster rate, so that by the time the shock reaches the end of the tube, it is not so strong. Thus, the reflected shock pressure, and ultimately the reflection deceleration, is smaller. Therefore, as shown in Figure 4, the initial deceleration increases with increasing specific heat ratio, while the reflection deceleration decreases.

2. Sound Speed

Decreasing the sound speed increases the Mach number of the flow, thus increasing the initial shock strength. This change produces effects similar to increasing the specific heat ratio; hence, a gas with a smaller initial sound speed produces a higher initial deceleration and a lower reflection deceleration than a gas with a higher sound speed. This behavior is shown in Figure 5.

3. Pressure

As shown in Figure 6, increasing the initial tube pressure has an effect similar to increasing the specific heat ratio and decreasing the sound speed. The initial deceleration increases with increasing initial pressure, while the reflection deceleration decreases.

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[2] The initial sound speed is evaluated at 530°R. The specific heat ratio is also evaluated at this temperature and is assumed to be constant throughout the calculations.
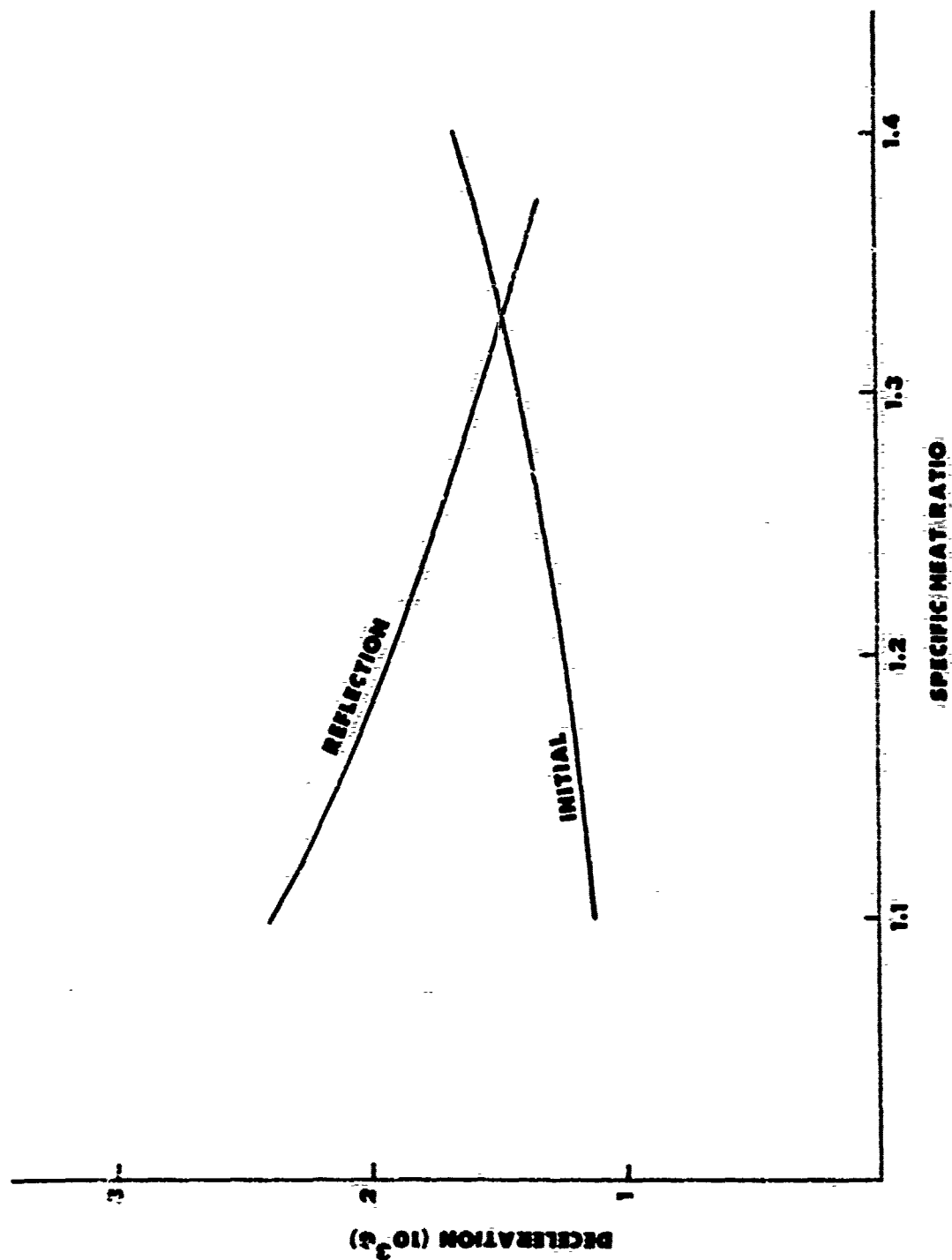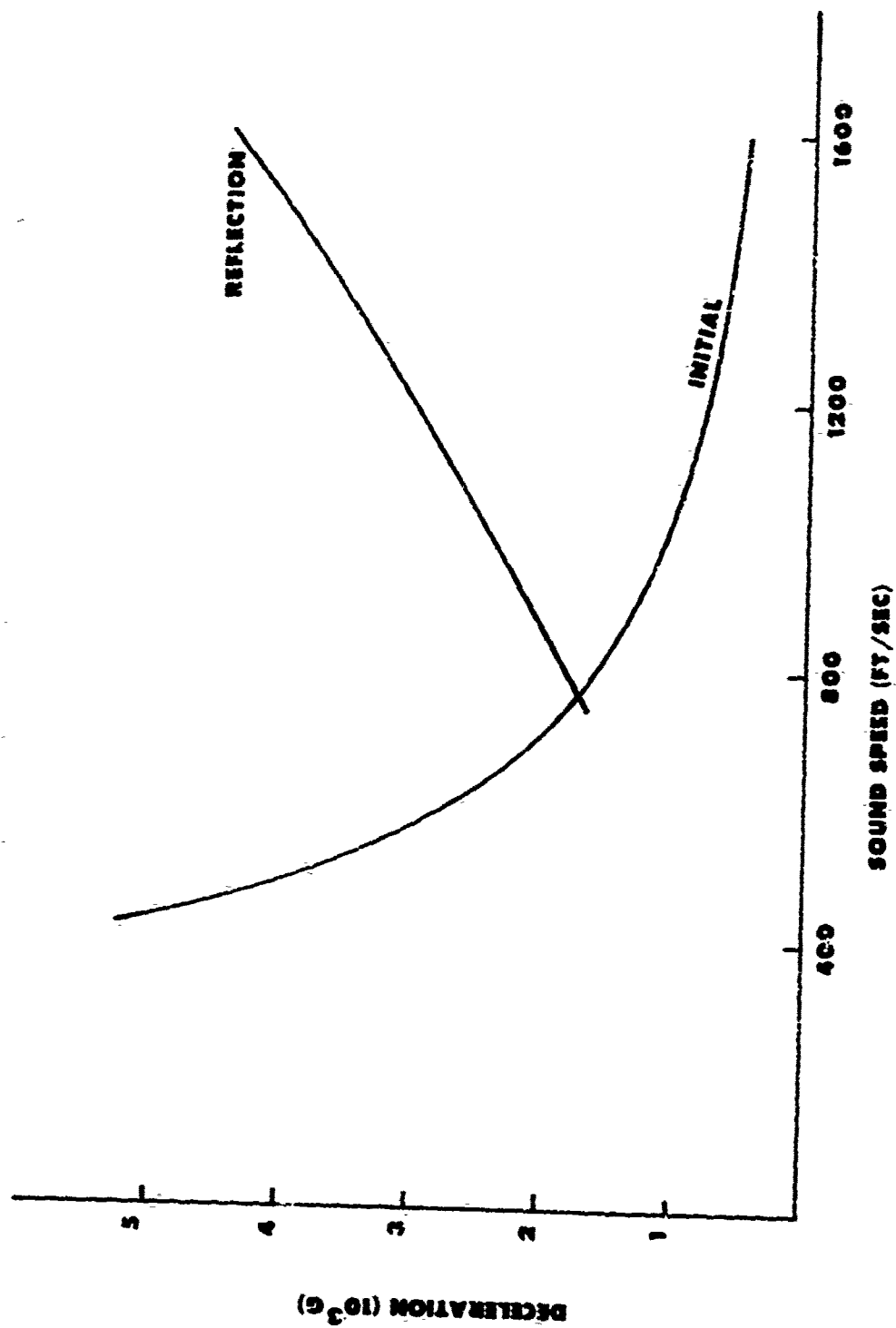
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REFLECTION

INITIAL

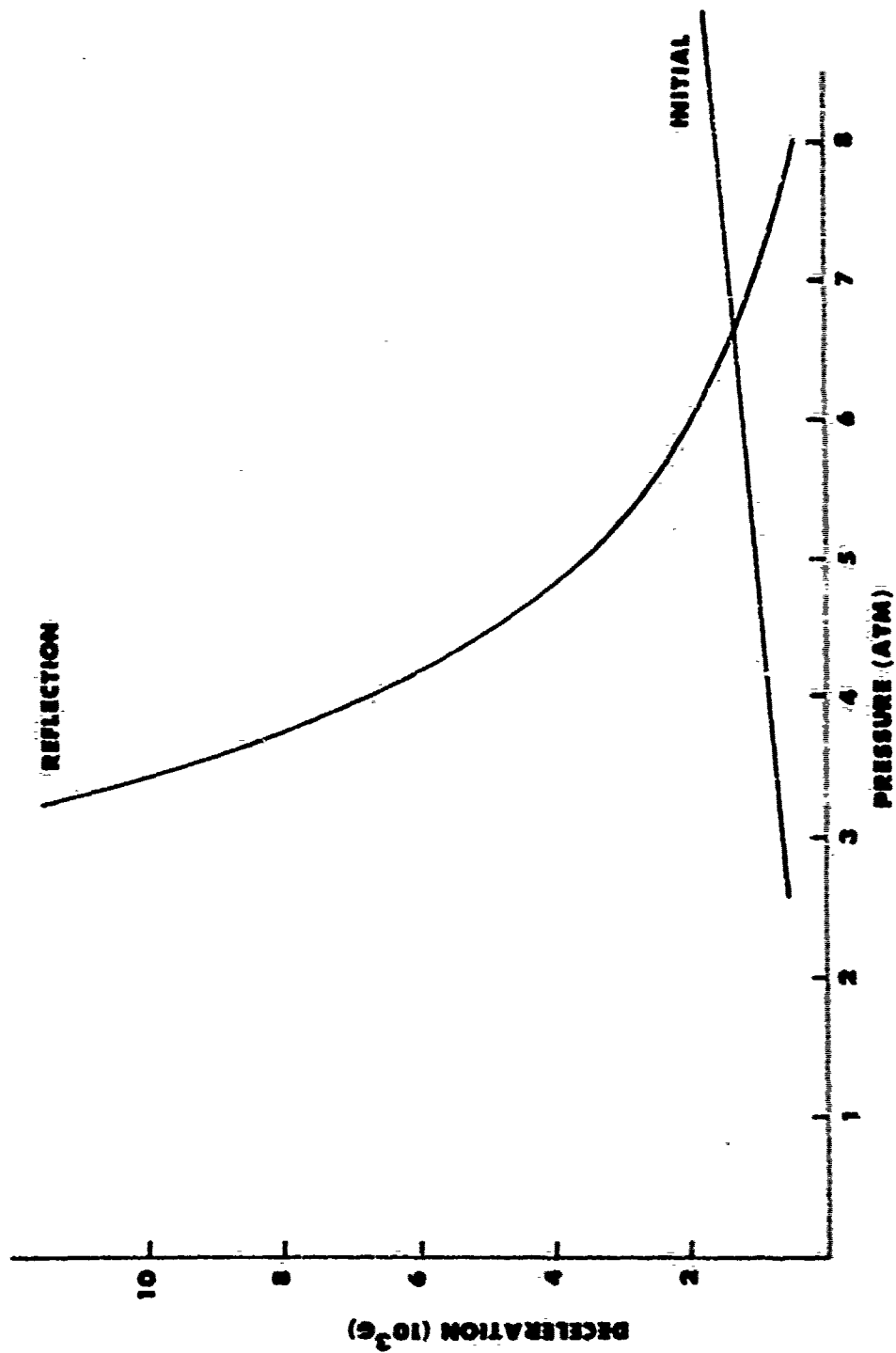SPECIFIC HEAT RATIO

DECELERATION (10^3 ft)

DECELERATION VS SPECIFIC HEAT RATIO

FIGURE 4

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SOUND SPEED (FT/SEC)

DECELERATION VS SOUND SPEED

FIGURE 5

DECELERATION (10³ G)

REFLECTION

INITIAL

10

DECELERATION VS INITIAL TUBE PRESSURE

FIGURE 6

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4. Tube Length

As shown in Figure 7, increasing the length of the tube affects only the reflection deceleration. Since the shock wave in front of the projectile has a longer distance to travel, it is weaker when it reaches the closed end. Thus, the shock reflected from the end of the tube is weaker and finally the reflection deceleration is smaller.

D. Determination of Optimum Parameters

In each of the above graphs, there exists a point where the maximum deceleration is minimum. This condition occurs when the initial deceleration equals the reflection deceleration. Therefore, any one of the four parameters being studied could be used as a basis for optimization. In this analysis, tube length will be chosen as the optimization parameter. The optimization procedure, then, is to determine the length of tube necessary to produce a reflection deceleration equal to the initial deceleration while keeping the initial pressure, the specific heat ratio, and the sound speed, constant. Of course, specific heat ratio and sound speed are physical properties of the recovery tube gas and are not independent of each other; however, several gases may have the same specific heat ratio but different sound speeds.

1. Determination of Initial Tube Pressure

Before the computer program can be used to determine the optimum tube length, there has to be some criterion for selecting the initial tube pressure and the gas which will provide the proper specific heat ratio and sound speed. Figure 7 shows that as the initial deceleration increases, the optimum tube length decreases. Therefore, the initial deceleration is chosen as the maximum allowable (10% of the maximum in-bore acceleration) in order to have the smallest possible tube length. Once the initial deceleration is determined, a relation between initial tube pressure and shock strength is obtained from equation (2), thus,

$$\xi_i \, P_0 = P_s = P_b + \frac{M}{A} D_i \tag{7}$$

where ξ_i is the shock strength necessary to produce the acceptable deceleration, D_i, for a given initial P_0. The quantity P_s is the pressure behind the initial shock.

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DECELERATION VS TUBE LENGTH
FIGURE 7

DISTANCE (FT)

DECELERATION (13ʹ6)

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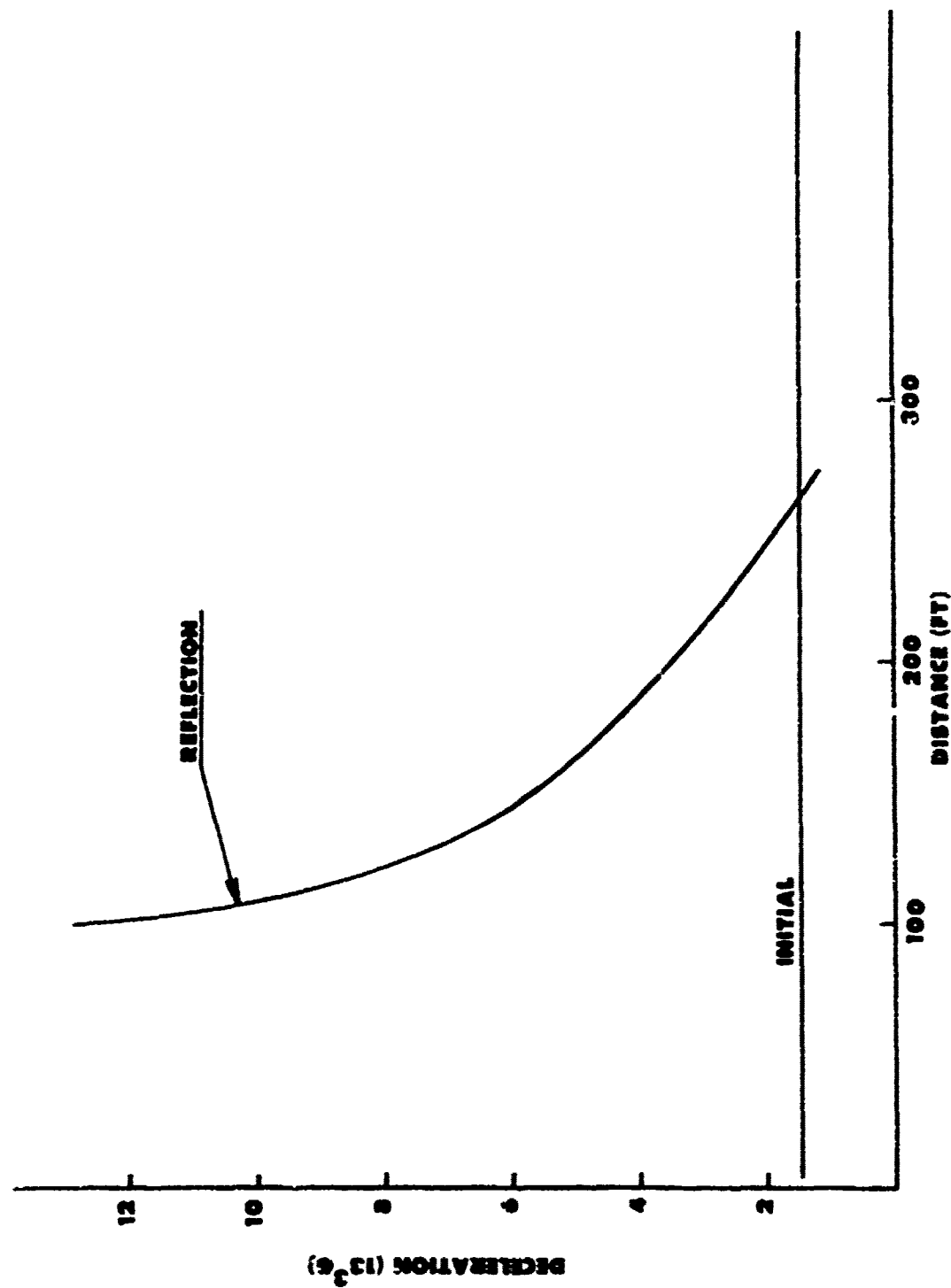
A standard 5"/54 projectile has a mass of approximately 70 lbs., experiences a maximum in-bore acceleration of approximately 15,000 g, and has a muzzle velocity of about 3000 ft/sec. The recovery deceleration should, therefore, not exceed 1500 g. This value is used for D_i in equation (7) to compute the pressure behind the shock. Thus, equation (7) shows that the initial shock strength is inversely proportional to the initial tube pressure. Since low initial tube pressures are desired, let an upper limit of seven atmospheres be set. Then according to equation (7), initial tube pressures of one to seven atmospheres are possible only if the shock strengths corresponding to those pressures are obtainable. Equation (1) shows that the shock strength is dependent only upon the specific heat ratio and the initial sound speed of the recovery tube gas, for given initial projectile speeds. Thus, it is now possible to determine the combinations of specific heat ratios and initial sound speeds necessary to produce the shock strength corresponding to any initial tube pressure. The properties of actual gases can then be examined to determine which ones, if any, have the proper specific heat ratio and initial sound speed combinations corresponding to any given initial tube pressure in the range of one to seven atmospheres.

2. Selection of Recovery Tube Gas

Since the shock strength for any given initial tube pressure is determined by equation (7), and the initial projectile speed is known, a relation between specific heat ratio and initial sound speed is obtained from equation (1). This equation can be rewritten in the form:

$$\frac{\left[\gamma + (\xi_i - 1) / 2(\xi_i + 1)\right]^2}{(\xi_i - 1)^2 / 4(\xi_i + 1)^2} - \frac{a_o^2}{U_p^2 / 8(\xi_i + 1)} = 1 \qquad (8)$$

This is the equation of a family of hyperbolas in the (γ, a_o) plane with the origin at $\gamma = - (\xi_i - 1) / 2(\xi_i + 1)$. Figure 8 shows curves for initial pressures of one, three, five and seven atmospheres. The curves are nearly linear over the range of specific heat ratios between 1.0 and 1.6. When an initial tube pressure is selected, the appropriate combinations of specific heat ratio and sound speed are determined from a curve defined by equation (6). Gases which have initial sound speeds and specific heat ratios close to the values on this curve are then selected for possible recovery tube use. The points shown in Figure 8 represent the properties of actual gases. Unfortunately, many of the gases, especially those located below the curve for five atmospheres, are not easily obtainable. However, many of the gases represented by points between the curves for five and for seven atmospheres are commercially available and include many of the
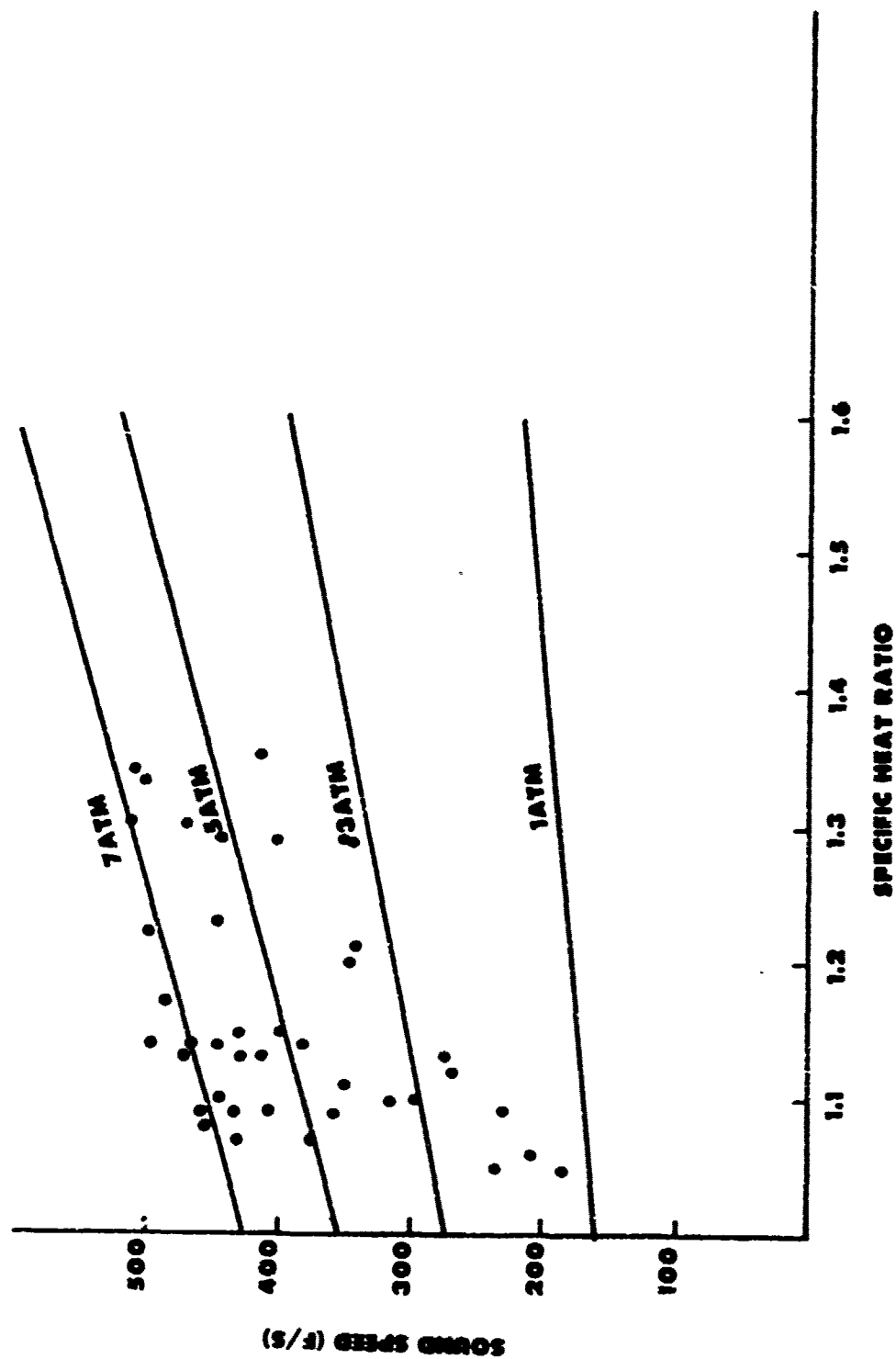
SOUND SPEED VS SPECIFIC HEAT RATIO FOR GIVEN INITIAL TUBE PRESSURES

FIGURE 8

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commonly used refrigerants. It appears, therefore, that the lowest
practical initial tube pressure is between five and seven atmospheres
although a more extensive study might be justified if lower initial
tube pressures are desired. Each of the gases that could be used at
initial pressures between five and seven atmospheres, has properties
which may make it either more, or less desirable than the others.
Hence, the final selection of a recovery tube gas should depend upon
a careful study of the individual characteristics of each candidate
gas. The most important characteristics to be considered are:

     a. Cost

     b. Availability

     c. Toxicity

     d. Deviation from a perfect gas

Characteristic (d.) needs to be considered because the analysis pre-
sented above assumes a perfect gas throughout. If the properties of a
gas differ greatly from those of a perfect gas, it may not be desirable
for use in the recovery tube even though it has suitable properties at
the beginning of the recovery process.

     Once a recovery tube gas has been selected and the
initial tube pressure has been determined by equation (7), the
optimum tube length can be determined by performing calculations for
several different tube lengths until one is found which gives a
reflection deceleration equal to the initial deceleration (1500 g for
the five inch projectile).

     The optimization procedure will now be illustrated for a
particularly promising gas, Sulfur Hexafluoride (SF_6). This gas is
available locally at $225 for a cylinder containing approximately
100 pounds. (The amount necessary to achieve the desired pressuriza-
tion for a 300 foot tube.) Sulfur Hexafluoride is chemically inert
and non-toxic. Sandia Laboratories (reference (3)) has used the gas
in their shock tubes and report a decomposition temperature of 2500°K.
This temperature is significantly greater than the 1800°K maximum
expected during the projectile recovery process. The compressibility,
$Z = \frac{PV}{RT}$, of SF_6 has been estimated from a generalized compressibility
chart to be between 1 and 1.15 for most of the temperatures and
pressures encountered during the projectile recovery.

The results from calculations of the maximum deceleration vs length for recovery tubes filled with SF_6 are plotted in Figure 9. The single curve shown in this figure is a composite of portions of the initial and the reflection deceleration curves. The optimum tube length occurs at the knee of this curve. The knee corresponds to a length of 300 feet and an initial pressure of 0.7 atmospheres.

Similar calculations were carried out using air as the recovery gas. Air used in place of SF_6 would give approximately the same optimum tube length, i.e., 300 feet, however, an initial pressurization of 30 atmospheres would be required. It is the low pressurization requirement that makes dense gases, such as SF_6, more attractive than air as a recovery tube gas.

III. RESULTS OF CALCULATIONS FOR A TUBE VENTED BY A PLUG

The simplified closed tube analysis of the previous section was useful in determining the effects of varying the initial sound speed, specific heat ratio, pressure, and the length of the recovery tube, on the deceleration of the projectile. This analysis is limited to closed tubes and cannot take into account the details of the gas flow between the shock waves and the projectile. To provide a more accurate model, a one-dimensional Lagrangian hydrocode was modified to calculate the motion of the projectile. The Lagrangian hydrocode is a finite difference computer program using artificial viscosity techniques to handle shocks. In this way the partial differential equations for motion of the gas are solved. The computer program is called SPREC. Although this program requires much more running time than the program mentioned in the previous section, it is more accurate and is able to calculate the effects of venting the gas in front of the projectile. Venting the high pressure recovery tube gas is necessary to prevent the projectile from reversing its motion and returning to the tube entrance where it would be difficult to have a soft recovery.

Venting could be accomplished in several ways; for example, a diaphragm placed at the end of the tube so that it would rupture when the initial shock reflected from it. The gas could also be vented, through orifices, into either the atmosphere or an external tank. A simple method of venting uses a projectile-like plug near the end of the tube. This plug would be designed to shear from its holder when the initial shock reached it. The gas pressure behind the plug would then force it out to the end of the tube, allowing the gas to vent to the atmosphere.

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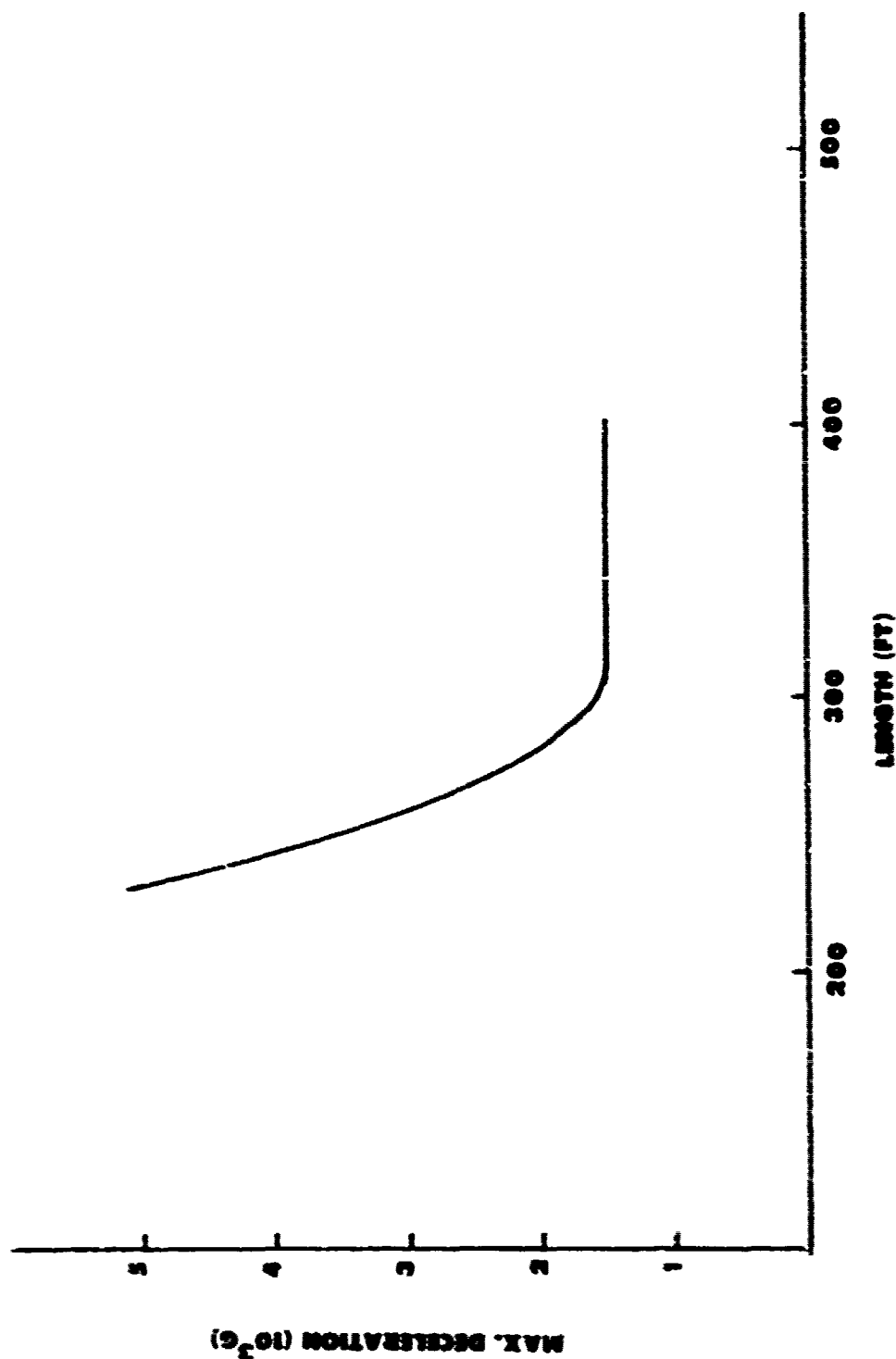
MAXIMUM DECELERATION VS TUBE LENGTH FOR SF$_6$ AT 6.7 ATM

FIGURE 9

The plug method of venting has been incorporated into SPREC to
calculate the projectile and the plug motions for various plug masses
and initial plug distances from the end of the tube. Using the informa-
tion provided in the previous section, computer runs were made for a
300 foot tube filled with SF$_6$ at an initial pressure of 6.7 atmospheres.
An optimum plug mass and an optimum distance were determined by moving
the plug from the end of the tube toward the entrance in various incre-
ments and then varying the mass until the projectile was stopped inside
the tube. The combination of plug mass and distance which have a
reflection deceleration equal to the initial deceleration, while
giving a small force on the projectile at the time of zero velocity,
was selected as the optimum condition. For this case, the optimum
plug distance is 260 feet from the tube entrance, and the optimum mass
68 pounds. (Nearly the same as the projectile.) Projectile decelera-
tion versus time for these conditions is shown in Figure 10. The plug
exit velocity is 1200 ft/sec.

The maximum gas temperature occurs near the front of the projec-
tile. This temperature is shown versus time in Figure 11 where the
largest value is seen to be 1800°K. The maximum pressure occurring
along the tube length is plotted versus time in Figure 12. This pres-
sure does not correspond to a single position in the tube, since the
point where the maximum occurs shifts around. The largest pressure
(11,000 psi) seen by the recovery tube (not the projectile) occurs
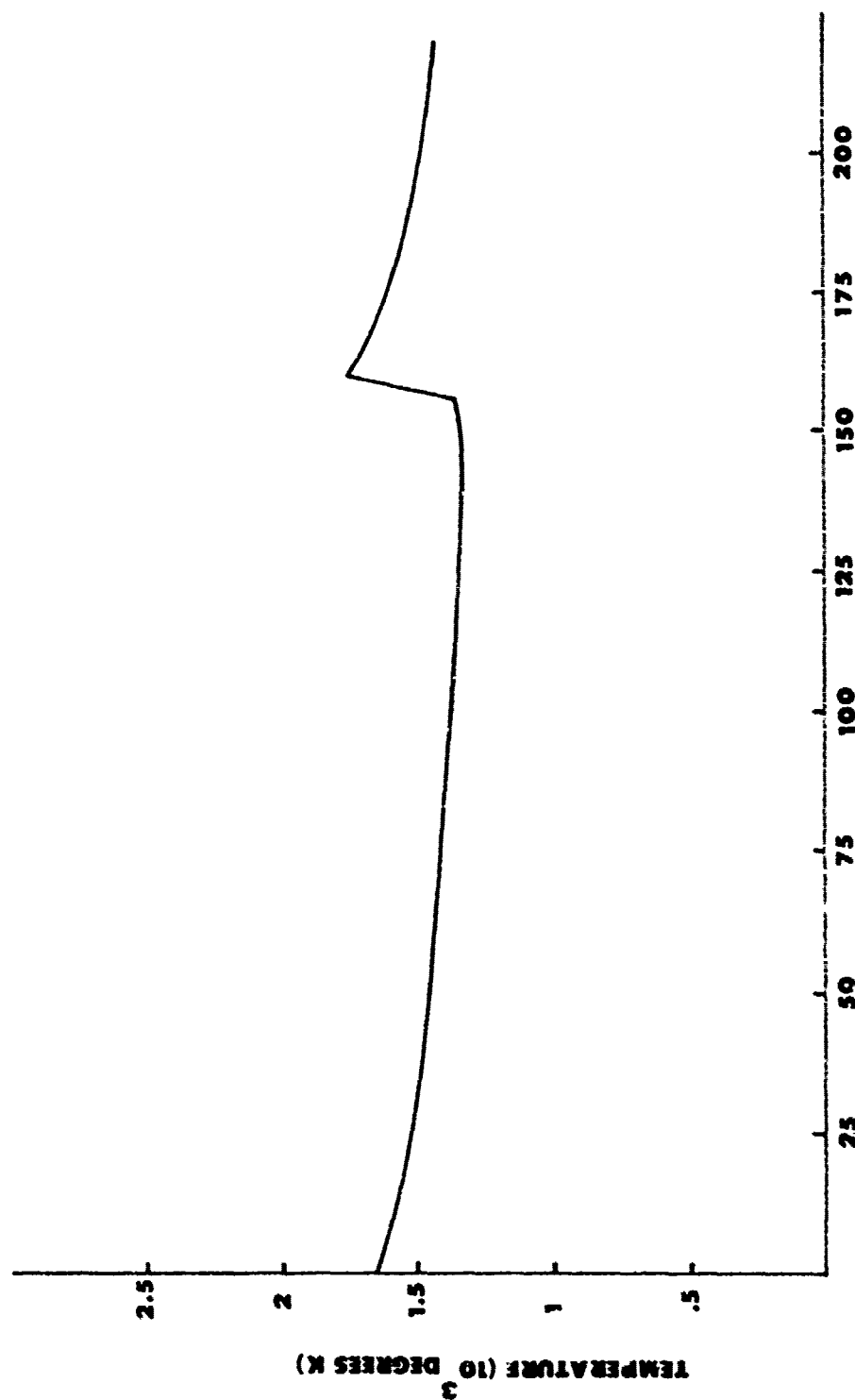when the initial shock wave reflects from the end of the plug.

IV. CONCLUSIONS

The results of the analyses described in this report indicate
that a pressurized tube could be quite successful in recovering a
five inch projectile with decelerations no greater than 10% of the
maximum in-bore acceleration. Approximately 300 feet of tube is
required to stop the projectile. An initial tube pressure of about
five to seven atmospheres is required if a dense gas such as Sulfur
Hexafluoride is used, and thirty atmospheres pressure is required if
air is used. It also seems feasible to use a plug near the end of the
tube, to vent the high pressure gas in front of the projectile. The
results of the computer analysis for a tube filled with 6.7 atmospheres
of SF$_6$ indicates that a 68 pound mass placed 40 feet from the end of
the tube would allow the projectile to stop without reversing its
direction.

Because of the limitations of the work described in this report,
further investigations are presently being performed. The most
important of these studies are:

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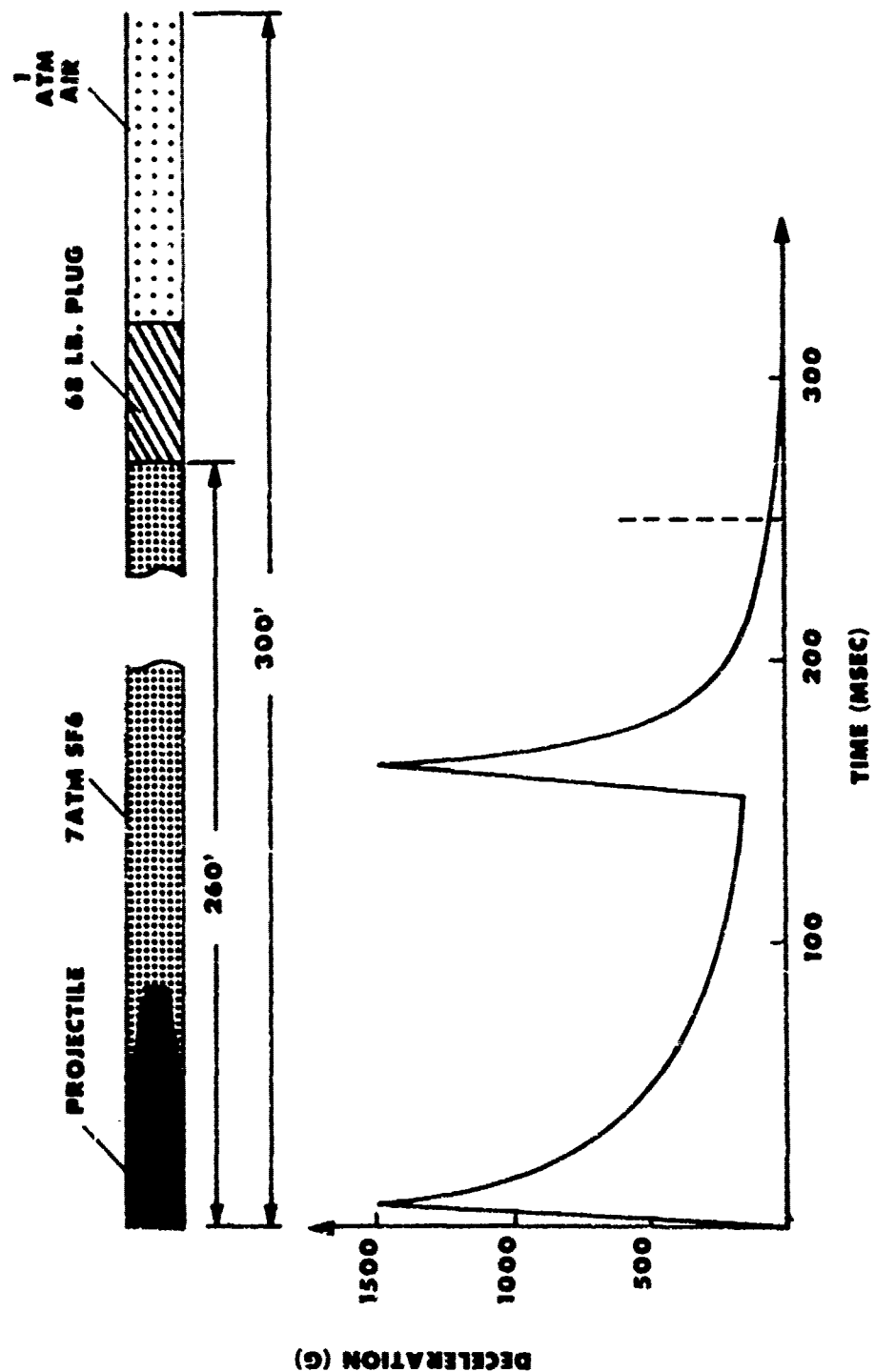
PROJECTILE DECELERATION VS TIME FOR A TUBE VENTED
BY THE PLUG METHOD
FIGURE 10

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MAXIMUM GAS TEMPERATURE VS TIME

FIGURE 11

TIME (MILISECONDS)

TEMPERATURE (10^3 DEGREES K)

21
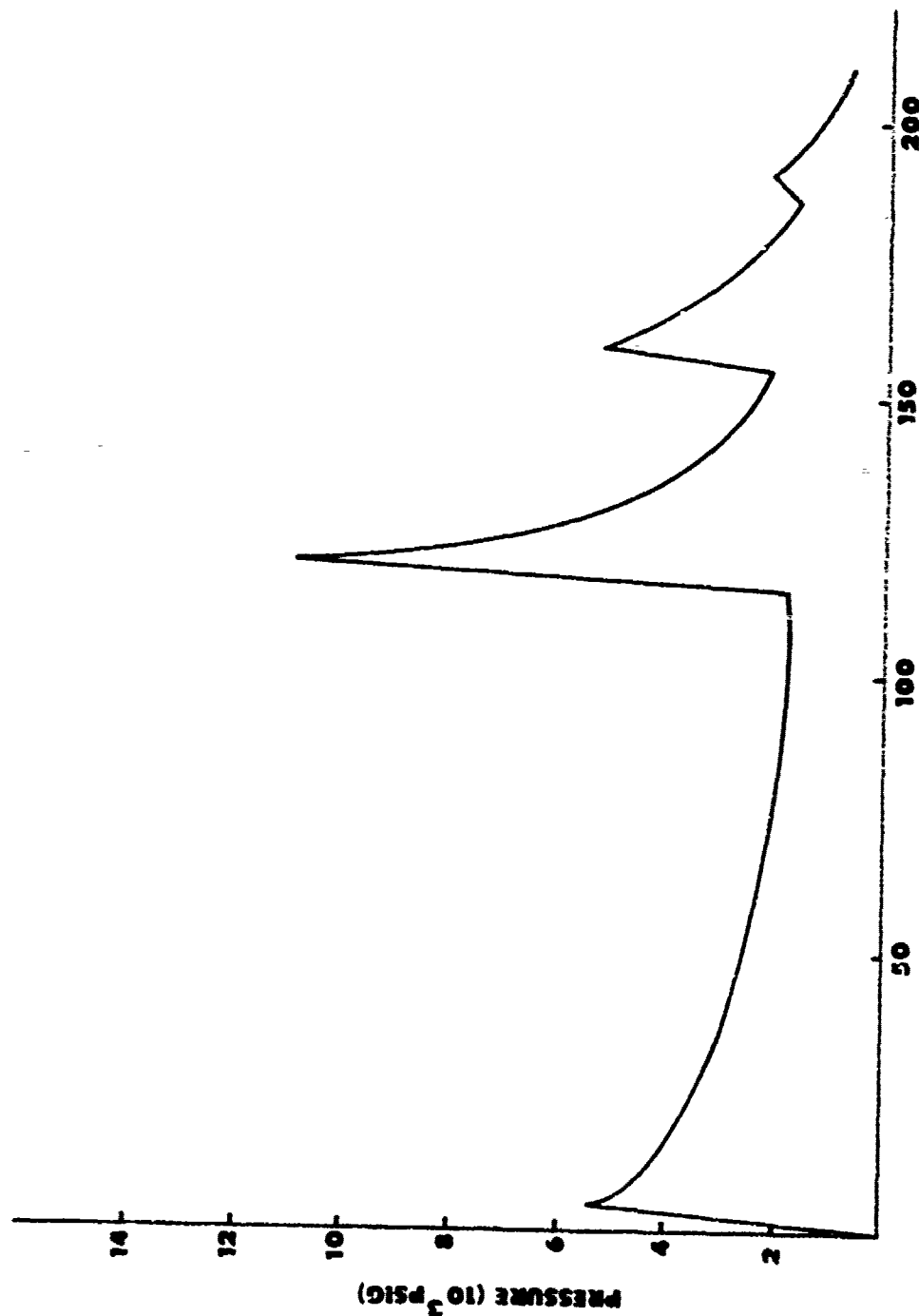
TIME ((MILISECONDS)
MAXIMUM GAS PRESSURE VS TIME
FIGURE 12

PRESSURE (10³ PSIG)

1. Effects of Venting the Propellant Gas Behind the Projectile

    The analysis assumes that the propellant gas pressure behind the projectile is atmospheric. The effect of venting the gas over a finite period of time and various methods of accomplishing this venting should be studied.

2. Effect of Leakage Past the Projectile

    A one-dimensional gas dynamics analysis indicates that as much as 8.2% of the initial mass of the recovery tube gas could be lost from leakage through grooves in the rotating band. The effect of this leakage on recovery tube performance and means of preventing it should be investigated.

3. Effects of Heat Transfer and Friction

    The analysis neglects all heat transfer and frictional effects. These effects should be investigated and the necessary corrections to the recovery tube design parameters should be obtained.

4. Effects of Balloting

    Balloting of the projectile traveling in the recovery tube has not been considered. This motion should be investigated to determine if it is large enough to affect the recovery tube design, and to determine the effects of transverse motions on the projectile.

    All of the above considerations are currently being studied. The results of these investigations should lead to a practical design for a soft recovery tube facility.

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